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Field Baseflow Eluting SOM-Rich Sandy Soil to Exacerbate Non-Point Source Pollution of Lake Erhai, Southwest China

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Abstract: Excessive nutrient loss from farmland located on the west bank of Erhai Lake has resulted in significant non-point source pollution within the Lake Erhai basin. However, mitigating this issue proves challenging due to the intricate nature of soil properties and environmental factors. Here, during the rainy season in the Lake Erhai basin, we collected and analyzed soil profile samples, 35 topsoil (0–20 cm) samples, and more than 300 field baseflow samples. Our objective was to explore the influences of soil properties, field baseflow, and agricultural management measures on the spatiotemporal migration of nutrients. The results indicated that the concentration of soil organic matter (SOM) has a significant impact on the spatial patterns of nutrient distribution in sandy soil. Consequently, this leads to a substantial reduction in the potential for nutrient loss in the Lake Erhai basin. The vegetable-field baseflow exhibited the highest concentrations of nitrogen and phosphorus when subjected to high fertilization and flood irrigation. The concentrations of TN and TP in baseflow increase by a factor of 2 and 7.7, respectively, during rainfall compared to periods of no rainfall. Optimizing agricultural measures, such as replacing chemical fertilizers with organic fertilizers and modifying irrigation methods to enhance the organic content of sandy soil and minimize baseflow elution, has a beneficial impact on mitigating agricultural non-point source pollution in the Erhai Lake basin. The research results can enable us to have a more systematic understanding of the problem of non-point source pollution in the Erhai River Basin, and provide a theoretical basis for developing targeted agricultural non-point source pollution mitigation plans. Simultaneously, optimizing agricultural management models to strike a balance between agricultural economic development and ecological protection issues holds significant practical significance for managers.

Keywords: Lake Erhai; field baseflow; soil organic matter; nitrogen and phosphorus losses; non-point source pollution; ecohydrology

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1. Introduction

Anthropogenic activities of intensive agricultural production have resulted in excessive nutrient losses, threatening water and environmental security [1,2]. For rural settlements located on high-altitude plateau lakes with ecological sensitivity and vulnerability, the environmental problems are greatly complex and severe [3,4]. Although the water quality on the west bank of Lake Erhai is class II (Table S1), the water quality is continuously deteriorating due to intensive agriculture [5]. Previous reports revealed that nitrogen (N) and phosphorus (P) losses from agricultural cultivation account for 42.46% and 38.83% of the total nitrogen (TN) and total phosphorus (TP) non-point source pollution in Lake Erhai, respectively [6]. Nevertheless, this has never been effectively solved due to the intricate process of nutrient losses in Lake Erhai fields. Identifying the key control factors and the main pathways of nutrient loss in fields is therefore crucial to tackling agricultural non-point source pollution in the Lake Erhai basin.

Soil properties, agricultural management measures, field hydrology and environmental conditions can significantly affect nutrient losses in the field [7–9]. Sandy soil generally has a low water content and nutrient retention capacity due to the large gaps between sand particles and lack of soil adsorbents (e.g., soil aggregates, SOM) [10,11]. A previous investigation demonstrated that a sandy soil texture could increase leaching losses of NO_3^--N and phosphorus (P) by up to 91.14% and 25%, respectively, compared to the loamy soil [12]. Farmers commonly utilize a range of agricultural management strategies to enhance the water and nutrient retention capabilities of sandy soil. One such approach involves implementing cross-slope ridging techniques to mitigate surface runoff and minimize soil erosion [13]. Additionally, farmers employ the practice of substituting straw return and organic fertilizer to augment SOM content, thereby further improving the soil's ability to retain water and nutrients [14–16]. Inadequate agricultural practices, such as excessive use of chemical fertilizers, can lead to substantial nutrient losses in fields [17]. Flood irrigation and furrow irrigation can also significantly increase soil nutrient losses via field osmotic leaching and lateral flow [18]. Although flood irrigation, like rainfall, can quickly change field hydrological conditions in the field to replenish water losses [19], most will back into rivers or lakes through leaching or laterally preferential flow (e.g., baseflow) [20]. Infiltrating water and baseflow not only directly elute topsoil nutrients [21,22] but also destroy soil microstructure and reduce soil adsorption adsorbents to increase sandy soil nutrients losses during migration [13,23,24].

There are few studies that have systematically explored the soil properties of the Lake Erhai basin through soil profiles. Although many studies have elucidated the factors influencing nutrient loss in soil properties under a specific crop pattern [25], there are few systematic studies on the variations in field nutrients under different agricultural management measures and the effects of field baseflow on soil nutrient loss in the Lake Erhai basin. In this work, by measuring soil physicochemical properties, investigating agricultural management practices, and conducting long-term baseflow monitoring in the Lake Erhai basin, we aim to address the following issues: (a) the influences of soil physicochemical properties on the spatial distribution of soil nutrients; (b) the differences in field nutrient losses under different agricultural management measures; and (c) whether field baseflow is a potential contributor to N/P nutrient loss. The research results will provide a theoretical and practical basis for optimizing planting modes and systematically solving the problem of agricultural non-point source pollution in Lake Erhai.

2. Materials and Methods

2.1. Study Area

The sampling area is located on the west bank of Lake Erhai (25°40′ N, 100°12′ E), which is the second largest lake in Yunnan Province (Figure 1). The Lake Erhai region belongs to the subtropical plateau monsoon climate zone, with an annual average temperature of 15.7 °C and 1000–1200 mm of annual precipitation. The rainy season in the Lake Erhai area lasts mainly from June to October, accounting for approximately 85–90% of the annual precipitation, while the dry season lasts from November to May, accounting for approximately 10–15% of the annual precipitation. The west bank of Lake Erhai is a typical agricultural rural landscape, with the primary crops including vegetables, corn, rice, and tobacco, most of which may be sown throughout the year.

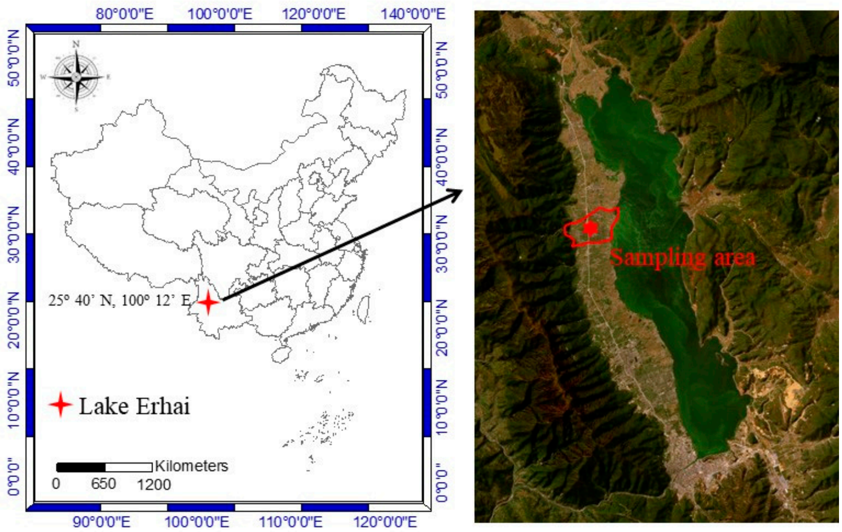

Figure 1. Sampling area on the west bank of Lake Erhai, Southwest China.

2.2. Methods

According to our field surveys, the typical planting patterns in the Lake Erhai basin include corn, rice, vegetables, and tobacco, which have great significance for the local agricultural economy and the protection of the ecological environment. In order to avoid interference with field management as much as possible, we sifted unreformed fields (Figure 2) that had screening requirements for the agricultural management measures for the same crop, including similar fertilization type, fertilization amount, cultivation method, irrigation method, etc. Therefore, we regarded fields with similar agricultural management measures as the repeated plots for typical crop (i.e., rice, corn, vegetables, and tobacco) field experiments. We pay more attention to the impact of different planting modes on soil nutrient loss from fields. The typical planting patterns with different agriculture management measures are therefore the treatments in this work. In order to avoid errors caused by environmental differences, our fields with the same crop are all within a linear distance of 200 m. In-situ observation in the selected fields were chosen for long-term field baseflow monitoring in order to better understand the variations in how field management practices affect nutrient loss in the fields (Figure 2 and Figure S1).

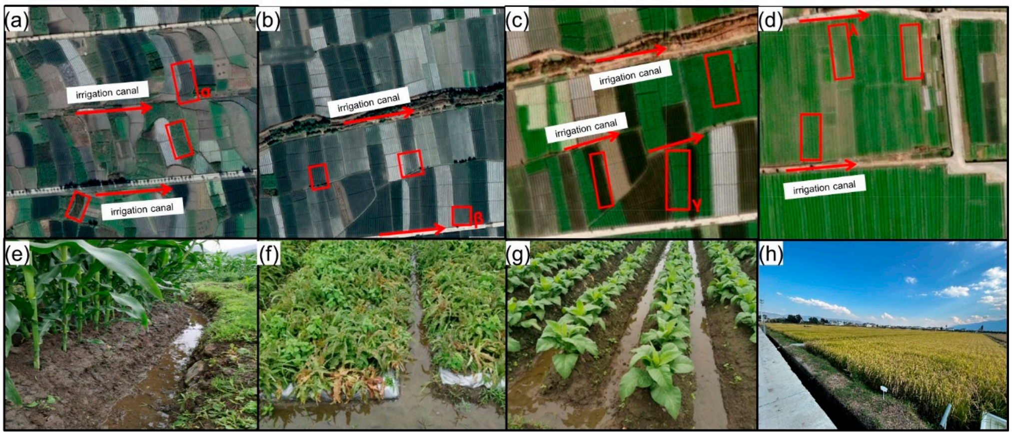

Figure 2. Distribution of long-term observation sites of baseflow in (**a**–**d**) surrounding soil profiles of sites 1, 2, 3 and 4 in Figure S1, respectively. Field photos of (**e**–**h**) of "α", "β", "γ" and "λ" in (**a**–**d**), respectively. The red rectangles represent the long-term observation fields of baseflow, and the red arrows are the irrigation canals.

Soil profile samples and ring knife samples were collected based on the soil generation layer during the excavation of soil profiles in different fields of the Lake Erhai basin. The linear distance between the topsoil (0–20 cm) sampling points and the soil profile sampling points in fields with four typical crops in the Lake Erhai basin did not exceed 200 m. Topsoil (0–20 cm) samples from four fields were collected using an S-shaped multi-point soil drill to sample the topsoil (0–20 cm). As spatial repetition, three sampling sites were arranged with a space interval of more than 100 m during sampling. At each sampling site in the tilled layer, soil samples were collected and mixed using S-shaped multipoints (0–20 cm). After collecting a fresh soil sample, crop stubble was removed and the sample was passed through a 2 mm sieve. After sampling, the samples were cryogenically preserved and transported to Yanting Purple Soil Agro-ecological Station for analysis. For the field baseflow samples, we conduct routine sampling of the on-site flow every 7 days and the sampling increases every time it rains. The sampling period for field baseflow started with the rainy season in the Lake Erhai basin (June to September 2022).

2.3. Measurements of Soil and Water Samples

The soil samples were divided into two parts according to the four-part method, one of which was stored in the refrigerator at 4 °C for leaching NH_4^+-N, NO_3^--N and DOC. Soil pH was measured in 1:2.5 (soil and water) suspension using a DMP-2 mV/pH detector (Quark LTD., Nanjing, China). Soil inorganic nitrogen (i.e., NH_4^+-N, NO_3^--N) was determined by 2 M KCl leaching soil. Soil was extracted with ultrapure water to determine the content of dissolved organic carbon (DOC) in the soil. Finally, an AA3 continuous flow analyzer (SEAL, Auto Analyzer 3, Germany) determined NH_4^+-N, NO_3^--N and DOC after filtration. Soil properties were obtained according to the standard method of measuring soil mechanical composition, TN, TP and other indicators [26]. The collected field baseflow samples were immediately loaded into the refrigerator for cryopreservation (0–4 °C) and transported back to the Yanting experimental station for nutrient concentration testing. Field baseflow samples were digested with an alkaline potassium (AK) persulfate solution and then analyzed together with filtering samples through a 0.45 μm membrane. The water properties, such as concentrations of TN, TP and NO_3^--N, were analyzed using the AA3 Auto Analyzer (SEAL, Hamburg, Germany) [27].

2.4. Statistical Analysis

The significance of the differences in variables was determined using the Waller–Duncan rank sum test, which was performed using SPSS software (version 2022). Origin software (version 2018) performed linear fitting of the correlation between SOM and the various nutrient elements. Plots were generated using Origin software (version 2018). The p values were calculated by the Origin software (version 2018).

A univariate linear regression model was employed to estimate the relationship between SOM and soil nutrients (Equation (1)):

$$y = ax + b \tag{1}$$

where "a" and "b" are model parameters and "x" and "y" indicate independent variables and dependent variables, respectively. In order to estimate the relationship between the spatial distribution of soil nutrients and SOM, we used corrections (Pearson's R) across different depths in soil profiles (Equation (2)):

$$R(x,\ y) = \frac{Cov(x,y)}{\sqrt{Var[x]Var[y]}} \tag{2}$$

where "$Cov(x,y)$" and "$Var[x]$" represent covariance and variance, respectively.

3. Results

3.1. Spatial Distribution Characteristics of Soil Physicochemical Properties

Soil profiles were divided three layers based on the soil taxonomy classification method: 0–30, 30–50 and >50 cm (Figure 3a). The soil texture in Lake Erhai basin from Cangshan to Lake Erhai is highly sandy and silty at different depths of the soil profiles, which together account for more than 80% of the total content. Large pebble and plow layers emerged below 50 cm of the soil (Figure S2), which are typical characteristics of the profile structure of alluvial and paddy soils. The existence of permeable water below the gravel layer in the soil profile indicated the presence of a shallow groundwater aquifer (Figure S2). Our results are consistent with the previous reports on soil texture in Lake Erhai basin, not only showing characteristics of sandy loam (with sand and silt content ranging from 79.6% to 91.98%) but also the highest organic matter content of up to 74.86% based on a comparison of soil texture at different sampling points (Table 1).

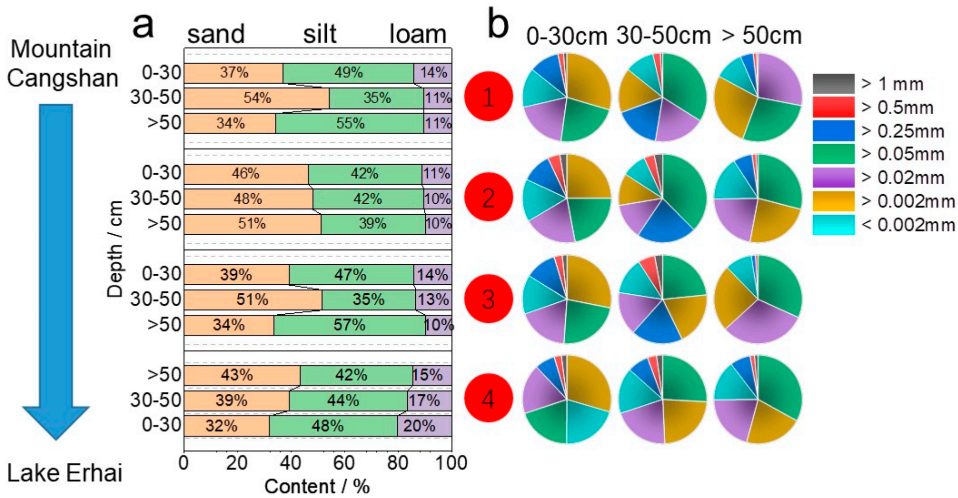

Figure 3. (**a**) Soil texture of profiles at different depths. (**b**) Particle size percentage for soil particles at different depths. Soil profiles 1–4 are distributed from Mount Cangshan to Lake Erhai. The pie chart is graphed in order of proportion, and the specific data are referred to in Table S3.

Table 1. Soil properties in previous studies of Lake Erhai. The locations of soil samples are marked in Figure S3.

References	Crop Types	Sand/%	Silt/%	Loam/%	SOM/g kg^{-1}
[24]	--	35.86	49.31	15.17	--
[28]	vegetable	35.02	56.89	8.09	59.87
	Rice	33.73	45.87	20.4	--
[29]	Corn	53.49	35.34	11.17	--
	Tobacco	29.92	56.32	13.76	--
[30]	--	43.45	43.71	12.84	74.86
		60.62	31.35	8.02	33.14
[31]	Vegetable	34.91	56.76	8.33	60.36
[32]	Garlic	76.53	13.06	10.41	42.61

Soil particle sizes showed significant variation at different depths in the soil layer within the different soil profiles (Figure 3b). For example, small particles (<0.05 mm) remained consistent across different profile points, but the percentage of large particles (>0.5 mm) increased in soil layers closer to Erhai (Figure 3b and Table S3). The proportions of large particles (>0.25 mm) in sand grains increased with soil depth in profile 1, while the proportions of particles sized 0.25–0.05 mm and 0.05–0.02 mm also increased significantly. Conversely, the proportion of particles sized <0.002 mm in loam decreased with increasing soil depth (Figure 3b and Table S2).

SOM concentrations in 0–30 cm soil are higher than the subsurface soil layer (Figure 4a), which might be ascribed to the agriculture management measures of straw return and organic fertilizer application (Figure S4 and Table 2) [32]. The increase in soil particle size may be responsible for the decrease in SOM concentrations in deeper soil layers (Figure 1), which results in an expansion in soil porosity [33]. The concentration of TN decreased with increasing depth (Figure 4b), which might be ascribed to the lack of SOM in deeper sandy soil layers. Because NH_4^+-N is easily ingested by crops or evaporated in the form of NH_3, it is highly soluble in water, soil colloids have fewer anion adsorption sites, and the content of NO^--N in field baseflow is much higher than that of NH_4^+-N [34,35]. The concentration of TP decreases with increasing depth, due to the lack of SOM in deeper sandy soil layers for P retention. As for the decrease in AP concentrations (Figure S5c), this might be ascribed to the AP altering the insoluble phosphate (e.g., $Al(PO_4)_3$, $Fe(PO_4)_3$) under the increase of pH in deeper soil depth (Figure S5d) [36]. Additionally, the moisture significantly increased with increasing depth (Figure S5e), which may be due to the frequent interaction between soil and shallow groundwater [28].

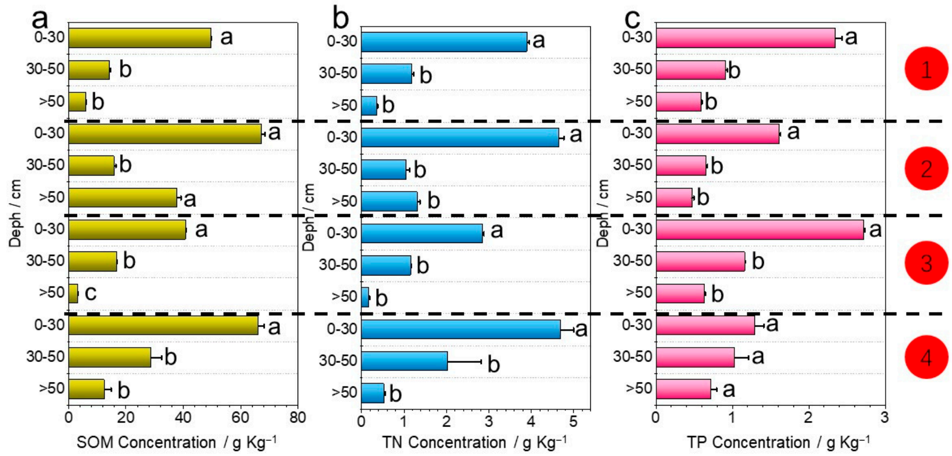

Figure 4. Soil nutrient concentrations of (**a**) SOM; (**b**) TN; and (**c**) TP in different soil depths. Profiles 1–4 are distributed from Mount Cangshan to Lake Erhai, with crops of corn, vegetable, tobacco and rice, respectively. Significant differences are noted using "a–c".

Table 2. Investigations of agricultural management measures.

Serial Number	Crop Types	Cropping Pattern	Irrigation Method	Planting Season/yr	Fertilization			
					Categories	Net Quantities/kg ha^{-1} Season		
						N	P_2O_5	K_2O
1	Corn	Ridge tillage	F	4	O/C	276 ^{b}	97 ^{b}	83 ^{b}
2	Vegetable	Ridge tillage	F	5	O	433 ^{a}	273 ^{a}	498 ^{a}
3	Tobacco	Ridge tillage	F	2	C	46 ^{d}	46 ^{d}	58 ^{c}
4	Rice	--	F	2	O	200 ^{c}	72 ^{c}	90 ^{b}

"1–4" indicates the serial number of soil profiles. "F" means the method of flood irrigation. "O" and "C" in the categories column indicate organic fertilizer and compound fertilizer, respectively. Detailed information on fertilizers is shown in Table S3. Different lowercase letters indicate significant differences between the net quantities of fertilization.

In order to understand the impact of SOM on the spatial distribution of soil nutrients, we analyzed correlations between SOM and topsoil nutrients (Figure 5). The correlation analysis showed that SOM had a significant correlation with the topsoil nutrients N, P, and potassium (K) in the soil ($p < 0.05$). The concentration of TN increased with the increase in SOM concentration (Figure 5a), which is due to the fact that SOM contains a large amount of organic nitrogen (ON), increasing soil N content through microbial decomposition. On the other hand, SOM not only has a large amount of organic colloids and a large specific surface area to directly adsorb soil nutrients but can also improve soil water retention and soil buffering capacity to reduce the leaching loss of soluble nitrogen (e.g., NO_3^--N, NO_2^--N) [37]. The concentration of TP showed a significant positive correlation with the SOM concentration ($p < 0.001$ in Figure 5b). SOM not only significantly enhances soil microbial activity to accelerate the transformation of soil mineral P but also contains a large amount of humic acid that increases the solubility of insoluble phosphates, thereby increasing soil phosphorus content [38]. The significant positive correlation between AP and SOM concentration also fully reflects the key role of SOM in soil phosphorus retention (Figure S6b). SOM can significantly enhance the buffering capacity of soil against changes in soil pH, keeping the soil pH near neutral (Figure 5c and Figure S6c) to be a beneficial soil environment for potassium retention [39]. SOM can increase the retention capacity of AK by increasing the negative charge of soil colloids and soil water retention capacity (Figure 5d and Figure S6d) [40].

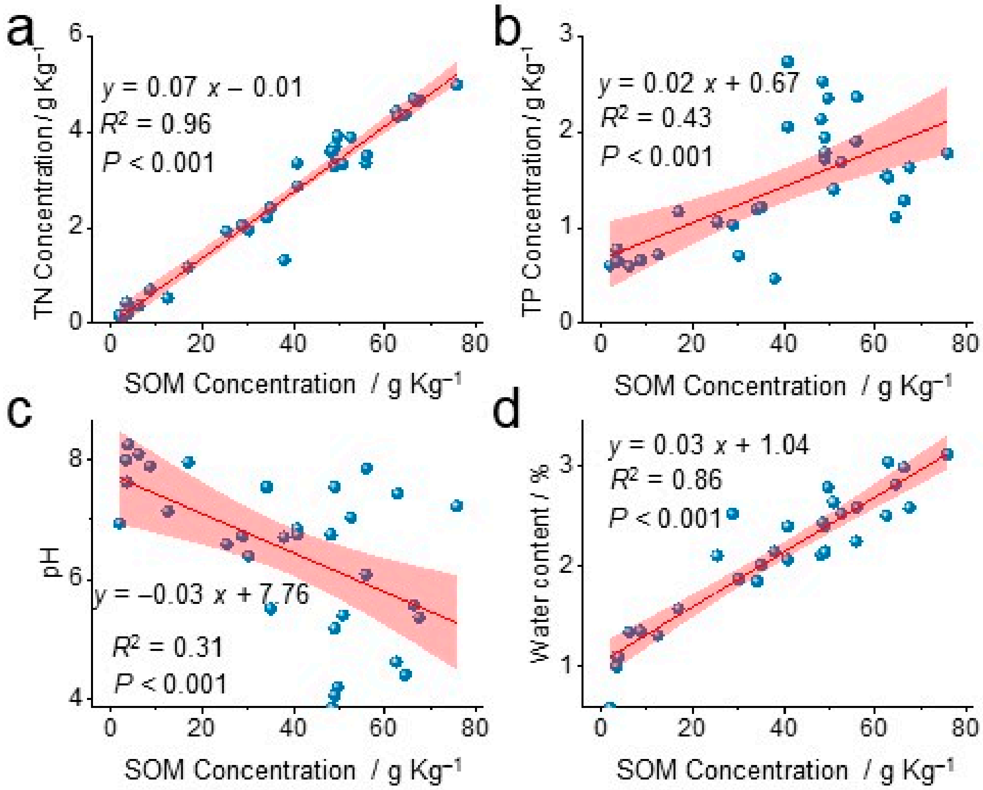

Figure 5. Correlation between SOM concentration with topsoil nutrients of (**a**) TN and (**b**) TP in soil. Correlation between SOM with (**c**) soil pH and (**d**) water content in soil. The red lines represent fitting lines. The pink areas indicate 95% confidence band. Significant difference was marked by "$p < 0.001$".

3.2. Nutrient Concentrations in Topsoil and Field Baseflow under Different Agricultural Management Measures

Planters in the Lake Erhai basin generally adopt the ridge cultivation and flood irrigation methods (Figure S7), and there are significant differences in the fertilization method (categories and amounts) in different crop fields on the west bank (Table 2). Organic fertilizer might be an effective approach for planters to increase SOM according to the investigation (Table 2), and the vegetable fields demonstrated the highest amount of seasonal fertilization, including N, P_2O_5 and K_2O net quantities of 433, 273, and 498 kg ha^{-1} season, respectively. On the contrary, tobacco fields have the lowest fertilizer levels of N, P_2O_5 and K_2O net quantities.

Topsoil samples from different crop fields were employed to further analyze the effects of different agricultural management measures on the nutrient variations in the field topsoil

(Figure 6). SOM concentration (Figure 6a) in vegetable fields (67.59 g kg^{-1}) was the highest among all field types (with concentrations of 65.47, 52.08, and 41.03 g kg^{-1} in paddy, corn, and tobacco fields, respectively). TN concentration (Figure 6b of topsoil in vegetable fields showed a highest value of 4.12 g kg^{-1} compared to other crop fields' (with concentrations of 4.03, 3.98, and 3.26 g kg^{-1} in paddy, corn, and tobacco fields, respectively), in which the order of AN concentration is consistent with the TN content: vegetable > rice > corn > tobacco (Figure S8a). The TP concentration of topsoil in vegetable fields was the highest, reaching 2.00 g kg^{-1}, which was only 0.07 higher than that of rice but much higher than that of corn (1.62 g kg^{-1}) and tobacco (1.32 g kg^{-1}) fields (Figure 6c). The concentration of available phosphorus in vegetables is still the highest (281.55 g kg^{-1}) compared to other fields (Figure S8b), but the AP in rice fields is the lowest (70.18 g kg^{-1}). This may be due to the fact that water needs to be added through flood irrigation during rice growth to compensate for evaporation and leachate, which increases the loss of soil colloidal phosphorus, or PO_4^--P through frequent elution (Figure S9a) [41].

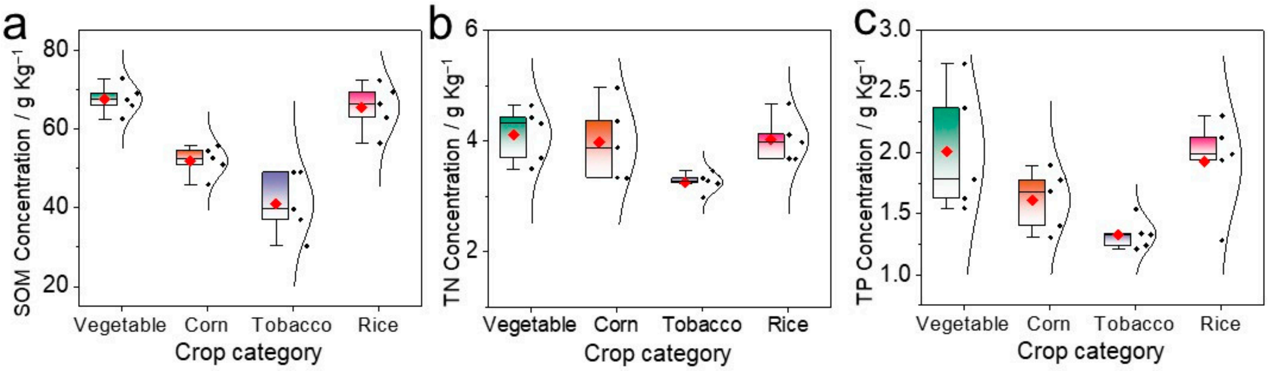

Figure 6. Concentrations of (**a**) SOM, (**b**) TN, and (**c**) TP in topsoil (0–20 cm) from vegetable, corn, tobacco, and rice fields. The red diamond indicates mean values. The solid line represents the median. The upper and lower boundaries of boxes are the percentage lines of 75% and 25%, respectively. The right arc represents the distribution of concentrations.

There is significant variance in nutrient concentrations in field baseflow (Figure 7). For instance, the dissolved organic carbon (DOC) concentration in paddy fields (8.21 mg L^{-1}) is about 2.32 times greater than in tobacco fields (with a lowest DOC concentration of 2.47 mg L^{-1}, Figure 7a). The TN concentration in the vegetable fields baseflow was found to be 5.88 mg L^{-1}, which was higher than in corn fields (4.85 mg L^{-1}) and 1.87 times higher than in paddy fields (2.59 mg L^{-1}). Field baseflow mainly transfers nitrogen from farming topsoil in the form of dissolved nitrogen (DN), and we found that TDN in baseflow from vegetable, corn, tobacco and rice fields accounted for 80.65%, 74.85%, 81.20% and 81.54% of the TN concentrations, respectively (Figure S9b). It is worth noting that the NO_3^--N concentration of baseflow in cornfields was the highest (3.06 mg L^{-1}, Figure S9c)—5.22 times higher than the one in tobacco fields (0.59 mg L^{-1}). This may be attributed to compound fertilizer application in cornfields (Table 2), which can provide a substantial quantity of nitrogen to the field in a shorter period of time than the organic fertilizers. The TP concentration in the baseflow of vegetable fields was the highest (0.66 mg L^{-1}), similar to the nutrient concentration in corn fields (0.61 mg L^{-1}), while the baseflow total phosphorus concentration was the lowest in tobacco fields (0.38 mg L^{-1}). Phosphorus in baseflow in farmland is mainly dissolved phosphorus (soluble phosphate), accounting for 77.27%, 54.10%, 52.63%, and 95.65% of the TP in the baseflow of vegetable, corn, tobacco and rice fields, respectively.

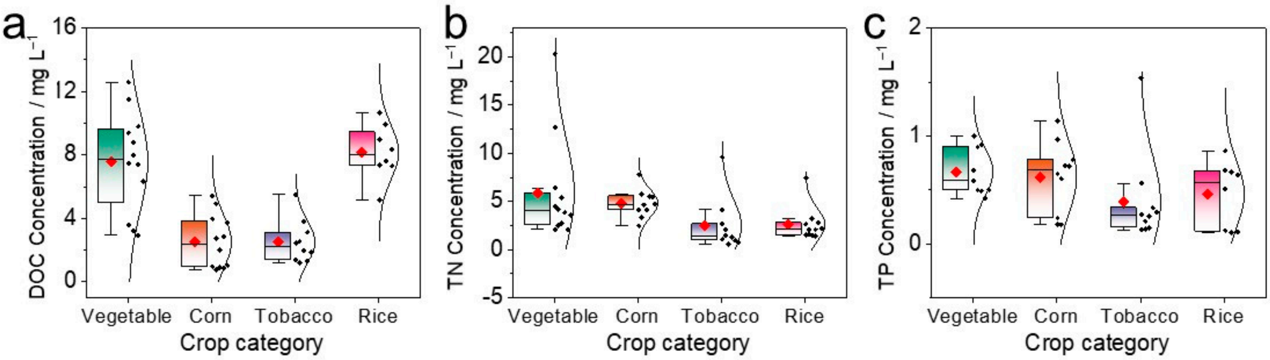

Figure 7. Concentrations of (**a**) dissolved organic carbon (DOC); (**b**) TN; (**c**) TP in vegetable, corn, tobacco and rice field baseflow. The red diamond indicates mean values. The solid line represents the median. The upper and lower boundaries of boxes are the percentage lines of 75% and 25%, respectively. The right arc represents the distribution of concentrations.

3.3. Nutrient Concentrations in Field Baseflow and Lake Erhai during Different Periods

Boosting baseflow can significantly exacerbate the loss of nutrients from the field (Figure 8). We documented a bloom of algae in Lake Erhai after a large amount of turbid water flowed into the lake after a heavy rainstorm on 1 July 2022. (Figure S10a), and then the temperature warmed up and a large-scale bloom occurred in Lake Erhai on 3 July 2022 (Figure S10b). The results of water sample measurements showed that the TN concentration of baseflow during rainfall (10.43 mg L^{-1}) is about double that during non-rainy periods (5.46 mg L^{-1}). It may be one of the main factors leading to a fivefold increase in TN nutrient concentration in the water of Lake Erhai during the algal bloom period (4.1 mg L^{-1}) compared to non-algal bloom periods (0.35 mg L^{-1}). TP concentration of baseflow during the rainfall (4.85 mg L^{-1}) is about 7.70 times higher than that during non-rainy periods (0.63 mg L^{-1}). This should be one of the main factors leading to a fivefold increase in TN nutrient concentration in the water of Lake Erhai during the algal bloom period (0.33 mg L^{-1}) compared to non-algal bloom periods (0.10 mg L^{-1}).

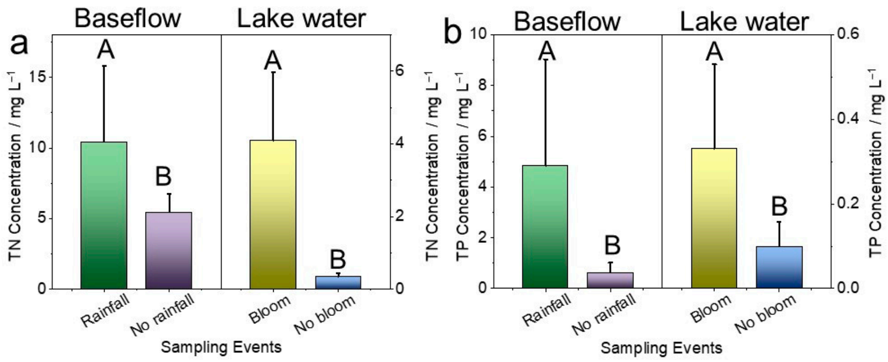

Figure 8. (**a**) Concentration comparisons of TN in baseflow and lake water during rainfall/no rainfall and bloom/no bloom, respectively. (**b**) Concentration comparisons of TP in baseflow and lake water during rainfall/no rainfall and bloom/no bloom, respectively. It rained on the west bank of Lake Erhai on 1 July 2022, and the bloom of Lake Erhai occurred on 3 July 2022. The significant differences are marked by "A" and "B".

4. Discussion

A typical structure characteristic of alluvial soil in the Lake Erhai basin is an obvious sandy soil texture [24], which greatly facilitates the migration of soil leachate and lateral flow to enhance the capacity of the soil nutrient transfer [10,33,42,43]. The total contents of sandy and silt in the soil in the Lake Erhai are more than 80%, which results in a lower ability to retain water and fertilizer because that sandy soil has rough particles, a low soil colloid content, and a fast infiltration rate. When field baseflow occurs in fields, nutrients are easily transported horizontally or downward with water, resulting in nutrient loss [29,33]. The shallow groundwater level is relatively high in the Lake Erhai basin, which can better promote the migration of nutrients in the sandy soil [44].

A high fertilization rate is essential to be inputted to compensate for the losses due to the low capacity of soil nutrients in the Lake Erhai basin. Due to the favorable hydrothermal conditions in the Lake Erhai basin, the high planting density and short growth period of crops require superfluous fertilizer input to meet their growth needs [28]. However, there are significant differences in crop cultivation and agricultural management measures in the Lake Erhai basin. Industrial crops (vegetables) usually require higher fertilization than food crops (rice and corn) due to their short growth cycle. However, the net N and P quantities input exceeding double that in vegetable fields compared to others also significantly increase the risk of dissolved N and P nutrients being lost with basal flow [17].

However, the influences of agricultural management measures on fields are extremely complex due to the physicochemical properties and nutrients retention of soil in the Lake Erhai basin [32]. For instance, ridge cultivation was extensively applied in Lake Erhai, which might be an effective approach to reducing the field baseflow elution caused by rainfall and flood irrigation [45]. The SOM content in the arable layer of the Lake Erhai basin is generally much higher than that in the subsurface soil due to the agricultural management measures of applying organic fertilizer and returning straw to fields. The correlation coefficients of p-values always below 0.001 indicate that there is a significant correlation with soil nutrient distribution characteristics [32]. SOM can not only improve the soil buffering capacity to resist acid–base changes to reduce the loss of salt ions [34,46] but also improves the soil water retention capacity by increasing soil clay to avoid the loss of nutrient solutes [47]. Nevertheless, the formed field baseflow, which is caused by the rough flood irrigation for compensating the water loss caused by high evaporation in fields in the Lake Erhai basin, can elute sandy soil in fields, carrying a large amount of nutrients to exacerbate agricultural non-point source pollution [21,42]. Meanwhile, the nutrient concentration of farmland basal flow during rainfall is double that of non-rainfall periods, indicating that local farmers should improve water conservation facilities to avoid soil nutrient loss caused by flooding in the field. Although SOM can help the sandy soil accumulate a large amount of nutrients, it also limits soil density and increases soil permeability, increasing the nutrient loss risk in fields [46,48].

5. Conclusions

This work explored the influences of potential factors that exacerbate non-point source pollution in the Lake Erhai basin. The results indicate that factors such as the texture of sandy soil can significantly increase field nutrient loss, but SOM increases soil nutrient content in topsoil (0–30 cm). Agricultural management measures of the high compound fertilizer input can greatly increase topsoil nutrient accumulation, expanding the nutrient loss load from fields in the Lake Erhai basin. Meanwhile, field baseflow caused by irrigation and rainfall further enhances soil nutrients loss via elution. For the local farmers, increasing SOM using organic fertilizer instead of chemical fertilizer and straw return in the fields is an effective approach to decreasing soil N and P losses via improving soil physicochemical properties. Furthermore, altering unsuitable field management measures such as flood irrigation and adjusting the planting model to balance economic and environmental benefits are essential for the healthy and sustainable development of agriculture in Lake Erhai. However, since Lake Erhai is a plateau lake with particular geographical conditions (such as photothermal conditions and microtopography climate) and soil parent materials from Mount Cangshan, agricultural management measures such as planting density and straw returning are not universally applicable to its watershed. This study focused on the effects of baseflow soil, interflow soil, and agriculture management measures on nutrient loss in fields in the Lake Erhai basin. To gain a deeper and more systematic understanding of agricultural non-point source pollution in Lake Erhai, further research on the strong interaction between groundwater and soil and longer in situ monitoring of baseflow are essential.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/horticulturae9080898/s1, Figure S1: Distributions of sample sites in the Lake Erhai basin; Figure S2: One of soil profiles of agricultural planting area in west bank of Lake Erhai; Figure S3: Locations of soil sample sites in literature surveys; Figure S4: One of soil profiles of agricultural planting area in west bank of Lake Erhai; Figure S5: Nutrient concentrations of (a) NH_4^+-N, (b) NO_3^--N and (c) AP in different soil depth. (d)Soil pH and (e) water content in different soil depth; Figure S6: Correlation between SOM concentration with soil nutrient concentrations of (a) AN, (b) AP, (c) TK and (d) AK; Figure S7: Pictures of the ridge cultivations in (a) tobacco and (b)corn fields and (c) flood irrigation in field; Figure S8: Concentrations of (a) AN and (b) AP in topsoil (0–20 cm) from different crops fields; Figure S9: Concentrations of (a) colloid, (a) TDN, (c) NO_3^--N, (d) NH_4^+-N, (e) TDP and (f) PO_4^--P in field baseflow; Figure S10: Photos of (a) confluence of Lake Erhai during rainfall on 07/01/2022 and (b) blooms in Lake Erhai; Table S1: Water quality grading in Yunnan province, China; Table S2: Percentages of soil particle size at different depths; Table S3: The information of fertilizers.

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